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Short-lived particle search procedure in the OPERA experiment. Application to charm decays

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Abstract

The OPERA experiment has recently provided evidence of $\nu_\mu \to \nu_\tau$ neutrino oscillations in appearance mode through the detection of tau leptons produced in ν_τ Charged Current interactions. The OPERA detector collected data from 2008 to 2012, when it was exposed to the CNGS muon neutrino beam from CERN to Gran Sasso, 730 km away from the source. We report on the search procedure for short-lived particles and on its validation with charmed hadron decays. The latter, produced in about 4% of the neutrino interactions in OPERA, are an important background to the $\nu_\mu \to \nu_\tau$ channel and an ideal control sample as their decay exhibits topological and kinematical features strongly resembling the tau's decay.

Keywords: neutrino oscillations, OPERA, tau neutrino, charm production in neutrino interactions

1. Introduction

Neutrino oscillations have been most often studied through neutrino disappearance results [1]. Recent appearance results [2, 3] have provided additional support for the reigning neutrino oscillation paradigm. In particular, OPERA's evidence for $\nu_\mu \to \nu_\tau$ neutrino appearance in the atmospheric sector [3, 4] confirms that the atmospheric ν_μ disappearance observed by SuperKamiokande [5] is due to $\nu_\mu \to \nu_\tau$ oscillations.

During 5 years of data taking, from 2008 to 2012, OPERA registered 19505 contained events corresponding to 18.0×10^{19} protons on target, whereas only about 60 ν_τ Charged Current (CC) interactions are expected to happen in the detector.

These CC interactions reveal the ν_τ appearance, as τ leptons are produced in the neutrino scattering off the OPERA target nuclei. Several hadron tracks are often also produced in primary interactions. Due to the high mean neutrino energy (17 GeV) and the τ lifetime, the τ lepton travels about 1 mm before decaying. Together with the fact that it decays nearly 85 % of the times to 1-prong final states, the typical ν_τ experimental signature consists of a track changing sharply its direction (a "kink"), attached to the interaction vertex together with other hadron tracks. In contrast, the dominant ν_μ interactions, whether they are mediated by Charged or Neutral Currents, produce most often a vertex of hadron tracks, partnered by a penetrating track (the muon) in the case of CC events. These events rarely exhibit a kink topology when only u and d quarks are involved. Charm production in ν_μ CC interactions occurs with a probability of about 4% and brings about an important background. Other than a muon track attached to the primary vertex, the topology of charmed particle decays is often nearly identical to that of τ decays, since the lifetime of charmed hadrons is very similar to that of the τ lepton and they also frequently decay to 1-prong final states. Therefore charmed hadrons are an excellent control sample to validate OPERA's vertex detection capabilities and efficiencies.

This paper summarizes the vertex reconstruction procedure employed in OPERA, and its application to the search for charmed hadron production in ν_μ CC events.

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More details can be found in a dedicated publication [6].

2. The OPERA detector

The OPERA detector, which is described in detail elsewhere [7], uses a hybrid technology: nuclear emulsions films and electronic detectors. Nuclear emulsions provide submicrometric resolution in position and an angular resolution of about 2 mrad. The purpose of the electronic detectors is to trigger, measure the properties of the penetrating tracks (most importantly, the muons' momentum and charge) and estimate the total energy deposited.

The OPERA target is arranged in units ("bricks") containing 57 nuclear emulsion sheets interleaved with 1 mm thick Pb sheets. There are about 150 000 bricks, amounting to a total mass of $1,2$ ktons. A brick weighs 8.3 kg and represents 10 radiation lengths. Two removable emulsion films, called "Changeable Sheets" (CS), are glued to the downstream face of each brick, their role being to confirm the presence in the brick of the tracks predicted by the electronic detectors.

Planes of plastic scintillator strips in between the brick walls allow to locate the brick where the neutrino interaction took place, extrapolating back to the CS the long, energetic tracks that cross several planes. A brick selected by the location algorithms is extracted, its two Changeable Sheets developed and scanned. If the tracks predicted by the electronic detector are confirmed in the emulsions, the whole brick is developed and automatically scanned.

The momenta of the tracks reconstructed in the emulsions are measured via their Multiple Coulomb Scattering in the lead plates [8]. The excellent angular resolution achieved by the nuclear emulsions allows to measure the dispersion of the angle of the track in each emulsion with respect to the global direction of the track in the brick. This dispersion is closely related to the momentum of the particle [1].

The OPERA detector also has some particle ID capabilities. Nuclear fragments are readily identified by the higher grain density along their tracks in the emulsions, a quantity related to dE/dx [9]. Electron tracks are identified through the electromagnetic showers they originate. Muons are selected with a 95 % efficiency by choosing long tracks that stretch over a sufficiently large range in the target [10].

3. The Decay Search procedure

Tracks reconstructed in the Changeable Sheets are automatically followed upstream ("scanback") in the brick. Either a vertex is found or the tracks disappear (they are not found in 5 consecutive emulsions. In the latter case, the most upstream track disappearance point is taken as a probable neutrino interaction vertex. A volume scan is performed around it, on a 1 cm^2 surface over the 5 emulsion films upstream of the vertex and 10 downstream of it. The "Decay Search" procedure is then applied:

- Extra track search. Additional event related tracks are selected among all tracks in the volume scan: if the track is at most 1mm away from the vertex, a maximum impact parameter (IP) of 300 μm is demanded, otherwise tracks must be closer than 3.6 mm to the vertex and have a maximum IP of 500 μm.

- Parent search. Tracks connecting the vertex and any downstream track not attached to the vertex are sought, with IP and distance to the downstream track smaller than 10 μm and 20 μm, respectively.

- Vertex recomputation. Visual inspection is used to recover scanning inefficiencies. Low momentum tracks as well as e^+e^- pairs are removed from the vertex definition. Tracks remaining with anomalous IP are investigated and undergo a new parent/partner search.

- Decay search along tracks. For small kink angles, parent and daughter tracks may be reconstructed as one continuous track. Kinks are looked for in the 4 films downstream of the vertex. The largest angular difference in these 4 films is compared to the RMS of the angular deviations along the whole track. If their ratio is greater than 5 and the kink angle greater than 0.015 rad, the kink is retained.

4. The charm control sample

Charmed hadron candidates have been looked for in data from the 2008, 2009 and 2010 CNGS runs by applying the decay search procedure described above. A charm candidate is detected whenever at least one of the charm daughter tracks is not attached to the primary vertex by the decay search procedure. The results have been compared to MC data produced with the standard OPERA simulation chain [11]. The charm production cross-section and fragmentation functions [1]

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[1] $\sigma(\nu_\mu N \to \mu C X) / \sigma(\nu_\mu N \to \mu X) = (4.49 \pm 0.26)\%$, $f_{D^+} = (21.7 \pm 3.4)\%$, $f_{\Lambda_c} = (25.3 \pm 4.9)\%$, $f_{D_s^+} = (9.2 \pm 3.8)\%$, $f_{D^0} = (43.8 \pm 3.0)\%$

Table 1: Summary of expected charm and background events, as well as observed events. The quoted errors include statistical and systematic uncertainties.

	Events			
Decay topology	Exp. charm	Exp. background	Exp. total	Obs.
1-prong	21 ± 2	9 ± 3	30 ± 4	19
2-prong	14 ± 1	4 ± 1	18 ± 2	22
3-prong	4 ± 1	1.0 ± 0.3	5 ± 1	5
4-prong	0.9 ± 0.2	-	0.9 ± 0.2	4
Total	40 ± 3	14 ± 3	54 ± 4	50

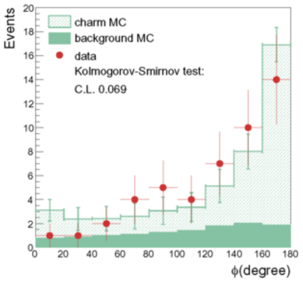

Figure 1: Shape comparison of charm data (dots with error bars) and MC distributions (histograms) of the angle ϕ between the candidate charmed particle and the primary muon in the ν transverse plane.

have been derived from the latest measurements from CHORUS [12]. An overall efficiency of $\epsilon_{\text{total}} = 0.34 \pm 0.04(\text{stat}) \pm 0.01(\text{syst})$ is predicted by the MC simulations. Background from hadronic re-interactions and decays of strange particles has been considered. The numbers of expected and observed charm candidates in the different topologies are in very good agreement (see Table 1), as are the shapes of the distributions of the relevant variables (see Figures 1 and 2; note that the MC distributions have been normalized to the observed number of entries in data.)

5. Conclusions

The decay search procedure used in OPERA to reconstruct short-lived particles, such as τ leptons, and the related reconstruction efficiencies determined from MC simulations were tested on a control sample. The chosen sample are charmed hadrons produced in ν_μ CC interactions, whose decays' topologies and kinematics closely resemble those of τ leptons. A very good agreement is found between the observed candidates in the data and the MC expectations, thus validating OPERA's τ search procedures.

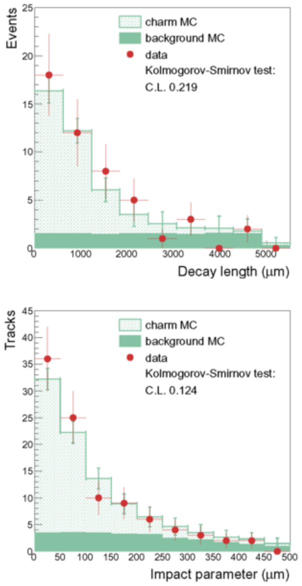

Figure 2: Shape comparison of charm data (dots with error bars) and MC distributions (histograms) of the decay length (top) and the impact parameter of the charm daughter particles with respect to the primary vertex (bottom).

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